Satellite Based Columnar Water Vapor Retrieval with the Multi-Spectral Thermal Imager (MTI)

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***Abstract*—The MTI has three near infrared bands, E, F, and G, within the 850 - 1050 nm spectral range, that are used for the columnar water vapor (CWV) retrieval using the continuum interpolated band ratio (CIBR) and the atmospheric precorrected differential absorption (APDA) methods. The retrieved CWV amounts are compared with the AERONET (aerosol robotic network) measurements at the Oklahoma Atmospheric Radiation Measurement (ARM) program and the Stennis Space Center sites. We find no significant difference in the accuracy of the two tested methods. However, there is a considerable difference in the root mean square error (RMSE) for the CWV retrieval over the Oklahoma ARM and the Stennis Space Center sites. The overall RMSE of the MTI CWV retrieval is found to be 13 to 14%. The error is reduced to 11 to 12% for CWV amounts larger then 1g/cm^2.**

***Index Terms*—Atmospheric measurements, remote sensing, satellites, water vapor.**

I. Introduction

Water vapor is an important variable constituent of the atmosphere. It plays a major role in redistribution of water and energy within the global atmosphere-land-ocean system. The annual average of columnar water vapor (CWV) varies between 0.25 g/cm^2 in Polar regions to over 5 g/cm^2 in tropics [1].

Several methods have been developed to estimate columnar water vapor amount (often also called the precipitable water (PW)) using the reflected near infrared solar radiation. In the near infrared range (Fig. 1) between 850 and 1050 nm there are three major water vapor absorption bands [2] that can be used to estimate the amount of water vapor in an atmospheric column.

Satellite sensors that use the NIR bands for water vapor retrieval include the DOE Multi-spectral Thermal Imager (MTI) [3], the Medium Resolution Imaging Spectrometer (MERIS) [4], the Moderate Resolution Imaging Spectroradiometer (MODIS) [5], [6], the Modular Opto-electronic Scanner (MOS) [7], and the Polarization and Directionality of the Earth's Reflectance (POLDER) [8]-[11]. All these instruments use several (2 to 5) spectral bands located in the 850 to 1050 nm spectral region (hyperspectral instruments use often the water vapor absorption band centered around 1135 nm).

The basis of the NIR algorithms used for CWV retrieval is to measure the top of the atmosphere outgoing radiances within a chosen water vapor absorption band, and just outside this absorption. The ratios of out-of absorption and in absorption radiances are then related to the amount of water vapor along the path. A complication arises due to atmospheric aerosols and due to non-linear spectral variability of the ground reflectance. An effort to minimize the effects of aerosol and ground reflectivity leads to several variations of a simple ratio method.

The algorithms used for the CWV retrieval include the differential absorption (DA) method [4], the narrow and wide (NW) band ratio [12], the continuum interpolation band ratio (CIBR) method [5]-[7], [13]-[15], and the atmospheric pre-corrected differential absorption (APDA) technique [16].

II. The Multispectral Thermal Imager

The DOE Multispectral Thermal Imager (MTI) [3], a satellite based push-broom instrument, has been in polar orbit since Spring of 2000. MTI has 15 spectral bands, ranging from visible to long-wave infrared. Its nominal pixel ground sampling distance (GSD) is 5 m at visible wavelengths and 20 m in the infrared. This fine spatial resolution and a special cirrus detection channel at 1.38 μm eliminate most of the problems connected to unresolved sub-pixel cloudiness. The MTI

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instrument is well suited for measurement of local and regional scale environmental variables with a swath width of 12 km and capability to image up to 48 km long strips.

The MTI spectral bands used for the CWV retrieval are centered at 875, 940 and 1015 nm. The 940 nm channel (MTI band F) is near the center of the strong water vapor absorption band (Fig. 1) while the channels centered at 875 and 1015 nm (MTI bands E and G) are outside the absorption band, in the region of very weak water vapor absorption. To retrieve the columnar water vapor, we use the CIBR and the APDA methods. To avoid the CWV underestimation problem of CIBR over dark surfaces and noisy CWV estimates for APDA due to sensor noise we found it preferable to search for vegetated surfaces, which appear bright in the NIR. For a given image the MTI algorithm first finds a set of pixels with high NDVI (normalized difference vegetation index). The MTI retrieved total water vapor amount is an average over high NDVI pixels. The retrieval algorithms use the MODTRAN code to calculate the top of the atmosphere outgoing radiances. The accuracy of retrieval depends on a proper choice of MODTRAN standard aerosol.

III. Satellite and Ground Truth Data

To evaluate the accuracy of the MTI water vapor retrieval codes using the CIBR and APDA algorithms, we need to compare the satellite derived columnar water vapor amount (precipitable water) with "ground truth" measurements. Due to large spatial and temporal water vapor variability and due to a small pixel size of the MTI (20 m x 20 m for spectral bands used in the CWV retrieval) we need to compare the satellite derived CWV with independent data of known quality that are taken at the same location within a short time from the time of satellite image. For this purpose we use AERONET (aerosol robotic network) [17], [18] total column water vapor measurements at the Oklahoma ARM (Atmospheric Radiation Measurement program) and Stennis Space Center sites. The accuracy of AERONET level 2 and 1.5 data is about $\pm$ 10% [19]. Within the time span from June 2000 to July 2002 we have available 51 MTI clear sky or partially cloudy images (18 for Oklahoma ARM site and 33 for Stennis). Most of the images are taken within 20 minutes from the available AERONET CWV measurements.

IV. Results

For the AERONET sites used in this study, we use the level 2.0 or 1.5 (when 2.0 level data are not available) data. First we consider each of the sites separately to check the consistency of the results between individual sites.

For Oklahoma ARM site we have 18 MTI images. The total column of water vapor varies between about 0.4 and 4.8 g/cm^2 with an average value of 2.5 g/cm^2. There is a small negative bias (close to 1.5%) between the results obtained by the CIBR or the APDA algorithm with respect to AERONET CWV measurements (Fig. 2). We find that both of the tested algorithms, the CIBR and the APDA, perform equally well. This is not surprising since the CIBR for high reflectance targets approaches the transmission estimate for APDA. The total RMS error of retrieval is about 8.7% (with respect to the AERONET data) with either of the used algorithms (Fig. 3).

We also compare the total column amount of water vapor provided by the Global Data Assimilation System (GDAS) of the NOAA NCEP (National Centers for Environmental Prediction) with the AERONET measurements (Fig. 2). The GDAS data are available on 1^o x 1^o grid with a time step of 6 hours. The GDAS CWV for a grid box containing the Oklahoma ARM site shows a negative bias (about 9%) and the total RMS error (with respect to the AERONET data) of about 13%.

For the Stennis AERONET site we have 33 MTI images with the total column water vapor amounts between 0.4 and 6.4 g/cm^2 and an average CWV of 2.8 g/cm^2. For the Stennis site the CWV retrieved with the CIBR or the APDA algorithm has an average negative bias (MTI retrieved CWV is lower then the AERONET measurements) of 10.9 % and 7.5 % (Fig. 2). The RMSE retrieval error with respect to the AERONET data is 16.6 % for the CIBR code, 15.2 % for the APDA and 14.9% for the GDAS.

Combining the Oklahoma ARM and the Stennis site AERONET columnar water vapor data (Fig. 4) for validation of the MTI CWV retrieval leads to the RMS error of the retrieval of 14.2% using the CIBR code, and 13.1% using the APDA algorithm. A large percentage error usually occurs for cases of low water vapor amounts, even when the absolute error is quite small. Considering only the cases with the total amount of CWV over 1 g/cm^2, the RMS retrieval error is 12.0% for the CIBR and 11.0% for the APDA methods.

V. Use of the GDAS Atmospheric Profiles and of the MTI Retrieved Aerosol Optical Depth

The presented MTI total columnar water vapor retrievals were obtained using the MODTRAN 4.0 radiative transfer code using scaled MODTRAN standard atmospheric profiles. The profile used for each individual case was determined by considering the geographical location of the site and the appropriate season. We have also tested the use of the GDAS provided atmospheric profiles for each of considered images, instead of standard MODTRAN profiles. We have found no significant difference in total columnar water vapor retrieval.

The achieved MTI accuracy of the CWV retrieval of 11 to 14% (depending on the algorithm used and on the amount of CWV) is based on using the MODTRAN radiative transfer code with the MODTRAN standard aerosol models defined by the boundary layer visibility. In the retrieval code the appropriate aerosol model is chosen based on the geographical location of the considered site (rural aerosol with 23 km visibility range for the Oklahoma ARM and Stennis sites). Since the MTI is also capable to estimate the aerosol optical depth (AOD) [20], we have investigated the effect of using the MTI retrieved AOD for each separate image (the estimated accuracy of the MTI AOD retrieval is around 0.03) instead of the standard MODTRAN aerosol model. The use of the MTI retrieved AOD lead only to a minor improvement (less than 1%) in the accuracy of the CWV retrieval. Fig. 5 may explain why the effect of a more accurate AOD had only a small effect on the CWV retrieval. Here we have used one image with the retrieved visibility range of 33 km and CWV of 4.3 cm. We have applied the CIBR CWV retrieval algorithm with different values of assumed visibility range from 10 to 50 km. The change of visibility range between 18 and 50 km has a little effect on the retrieved CWV.

Consequently, the retrieved amount of CWV will not change in any significant way whether we use the standard MODTRAN aerosol with 23 km visibility range or a more accurate retrieved value of 33 km. It is only for visibility range < 18 km where the exact value of visibility range matters. Unfortunately, all our images have AOD between 0.03 and 0.42, which corresponds to the visibility range (assuming 2 km thick aerosol layer) between 18.6 and 43.5 km. Thus our CWV retrieval does not change significantly with the use of the MTI retrieved AOD instead of the standard MODTRAN 23 km visibility range rural aerosol model.

VI. Discussion and Conclusions

We have applied the CIBR and the APDA methods for total columnar water vapor retrieval to a set of 51 DOE MTI images. The retrieval results were compared to the AERONET columnar water vapor measurements at the Oklahoma ARM and Stennis sites. Only small differences between the CIBR and APDA algorithms were found. Both algorithms provided results of nearly the same accuracy. The RMS error of retrieval was 13 to 14% when all data from the Oklahoma ARM and Stennis sites were considered, and 11 to 12% for total column water vapor amounts larger then 1 g/cm^2. It is interesting to note that the estimated (modeled) accuracy for the MODIS total columnar water vapor retrieval (the MTI CIBR algorithm is similar to the MODIS CWV code) is around 13% [7].

It seems that the APDA method appears to provide a slightly higher accuracy than the CIBR method at both study sites. In addition, it appears that the accuracy of both methods is higher when applied at the ARM study site than at the Stennis Space Center site.

To test these two hypotheses we have considered the non-winter data (data with higher amounts of CWV) from both sites as a randomized block statistical experiment. There were 16 samples for the ARM study site and 15 samples from the Stennis site. The study site was used as the blocking factor. There was no significant difference between the CIBR and the APDA methods as applied at either study site (p-value = 0.3747). However, there was a significant effect when the site was used as a blocking factor (p-value < 0.0001). Therefore, the accuracy of retrieval using either method depends on which site is being studied.

The fact that we get an RMS error for the Oklahoma ARM AERONET site between 8 and 9%, while the RMS error for the Stennis AERONET site is between 15 and 17% is not easy to explain. The images of these two sites were taken during the same time period with the same instrument (the MTI) using the same retrieval algorithms (CIBR and APDA). A possible explanation of the discrepancy is that the accuracy of the two different AERONET instruments is not the same. Our results suggest the Stennis AERONET total column water vapor data may be systematically high by 5 to 10%. This is very probably due to differences in the calibration of the AERONET instrumentation at each site [21].

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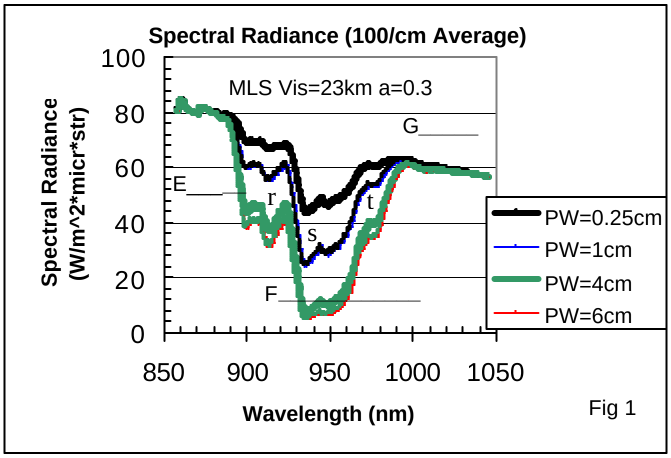
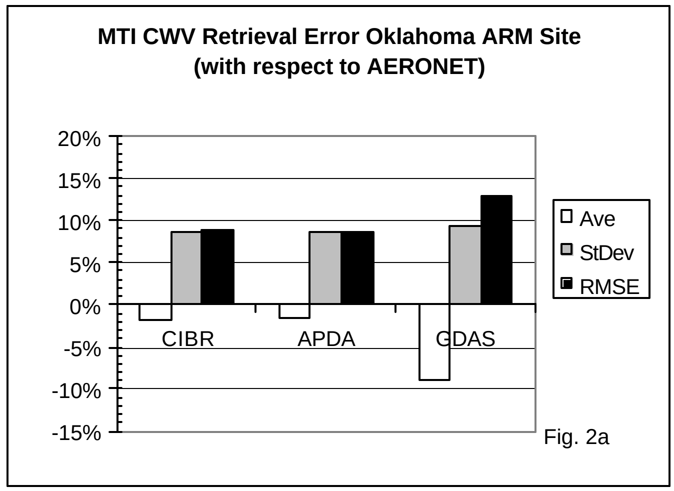


Fig. 1: Spectral radiance over the 850 to 1050 nm band (obtained using the MODTRAN 4.0 radiative transfer code) average over 100 cm^{-1} shows three major water vapor absorption bands (ρ, σ, and τ) together with the location of the MTI bands E, F and G used for CWV retrieval. The model calculations use the Midd-latitude Summer (MLS) atmospheric profile with rural aerosol visibility (Vis) of 23 km, the surface albedo of a =0.3, the solar zenith angle (SZA) of 30^o and satellite viewing angle of 0^o (a nadir view).



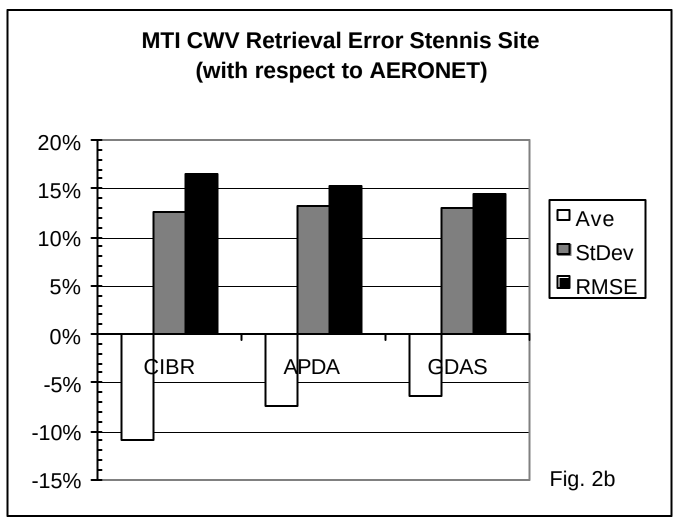


Fig. 2: The average error (Ave), the standard deviation (StDev) and the root mean square error (RMSE) of the CIBR and APDA CWV retrieval and the GDAS CWV data with respect to the AERONET measurements at the Oklahoma ARM (the upper panel) and the Stennis Space Center (the lower panel).

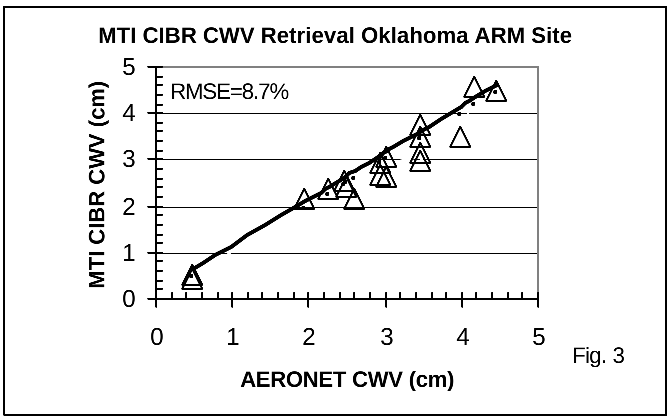


Fig. 3: The MTI CIBR retrieved CWV compared to the AERONET data at the Oklahoma ARM site.

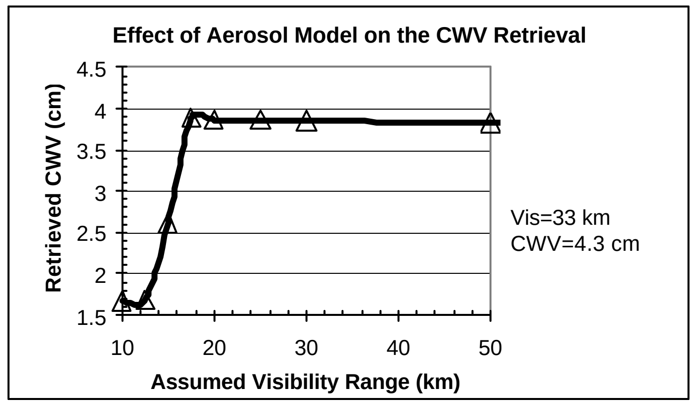


Fig. 5: Used aerosol model does not affect the retrieved CWV significantly for change of visibility range between 18 and 50 km.

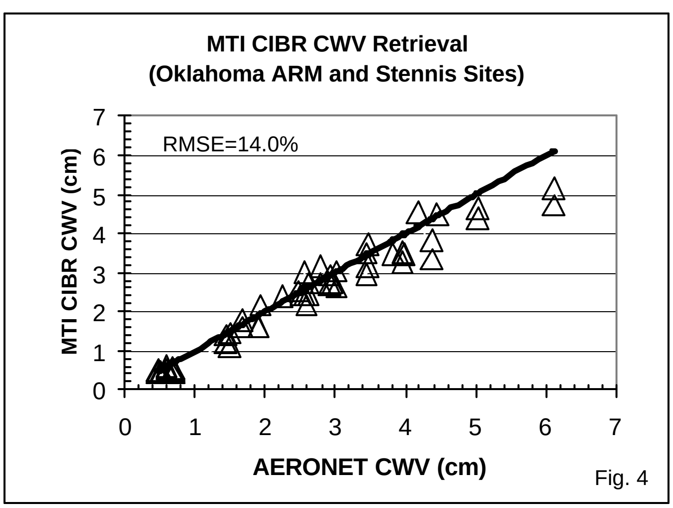


Fig. 4: The MTI CIBR retrieved CWV compared to the AERONET data at the ARM and Stennis Space Center sites.